Ground-Based Inerting of Commercial Transport Aircraft Fuel Tanks

William M. Cavage - Fire Safety Branch
Federal Aviation Administration
William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405

ABSTRACT

Extensive research has been performed by the Federal Aviation Administration to help develop practical and cost-effective inerting systems for commercial transport airplane fuel tanks. The concept of ground-based inerting has been studied in the laboratory and on two different aircraft in an attempt to develop a cost-effective methodology for fuel tank inerting. These research projects studied inert gas requirements, effects of adjacent fuel loads, oxygen concentration requirements, modeling of inert gas flow, and full-scale flight and ground center wing tank inerting. The results indicate that fuel tanks can be inerted efficiently with nitrogen-enriched air and that adjacent unscrubbed fuel loads would have very little effect on the inert ullage compared to the effect of fuel usage. Although some data illustrated that inert gas distribution could be problematic under some inerting conditions, results indicate that inerting was predictable and efficient and could be modeled, provided attention is given to vertical mixing. Aircraft inerted on the ground maintained a significant benefit during ground and flight operations, provided the vent system does not allow cross-flow through the tank.

INTRODUCTION

More emphasis has been placed on fuel tank safety since the TWA flight 800 accident in July 1996. The National Transporation Safety Board concluded that a center wing fuel tank explosion was the probable cause of the accident. Since the accident, the Federal Aviation Administration (FAA) has conducted a considerable amount of research into methods that could eliminate or significantly reduce the exposure of transport airplanes to flammable vapors. This includes research on fuel tank inerting, which is commonly employed by the military. Fuel tank inerting could be made more cost-effective if it focused only on center wing or body style tanks, which tend to be hotter during ground operation and more flammable in general [1], and if some method of ground-based inerting were used.

Ground–based inerting (GBI) is defined as inerting a fuel tank ullage on the ground, with either ground-support equipment or onboard systems, and then continuing ground and flight operations, which allows the ullage oxygen concentration to dissipate over time. Calculations indicate that this inerting methodology could keep the center wing tank (CWT) ullage inert during all ground and most flight conditions, depending on the length of the flight and the fuel load. Analytical models indicate that inerting of heated center wing tanks in this manner could reduce the average fleetwide exposure to flammable vapors from approximately 30 percent of flights to as little as 5 percent [2].

An extensive research program was initiated to study methods and requirements for inerting commercial transport airplane fuel tanks in a cost-effective manner. These research projects studied inert gas requirements, effects of adjacent fuel loads, oxygen concentration requirements, modeling of inert gas flow, and full-scale flight and ground CWT inerting.

PRELIMINARY RESEARCH

<u>Previous Research.</u> Methods of inerting fuel tanks have been studied since the late 1940s. Macdonald and Wyeth summarized different methods of inerting fuel tanks, including reduction of oxygen concentration with nitrogen (ullage washing) [3]. Klueg, McAdoo, and Neese evaluated a stored liquid nitrogen fuel tank inerting system on a DC-9 commercial transport aircraft [4]. The extensive work by Stewart and Starkman focused on the oxygen concentration reduction requirements and flammability limits [5]. This work illustrated flammability relationships and inert gas requirements but has a limited amount of experimental data and

predates modern fuels (JP-8 and Jet A). Kuchta detailed inerting requirements in various hydrocarbon-based fuels for different inerting agents and gave an analytical basis for some measured data [6]. The work predates Jet A and JP-8, but does have some kerosene data, and gives very little insight into the effect of altitude on the oxygen concentration requirements.

More recent FAA experiments focused on inerting of simple rectangular spaces, which have a single deposit nozzle and exterior vent, with nitrogen-enriched air (NEA) (figure 1). NEA is the term used to describe relatively impure nitrogen (99% – 92% nitrogen by volume), which is usually generated by a gas separation process. These data illustrated that a volumetric tank exchange (VTE) of 1.5 to 1.6 would be required to inert an ullage (empty space above fuel surface) to 8% oxygen concentration using NEA 95 (95% nitrogen, 5% oxygen) [7]. In other words, to inert a tank to 8% oxygen by volume, you need 1.5 to 1.6 times the volume of the ullage of NEA 95.
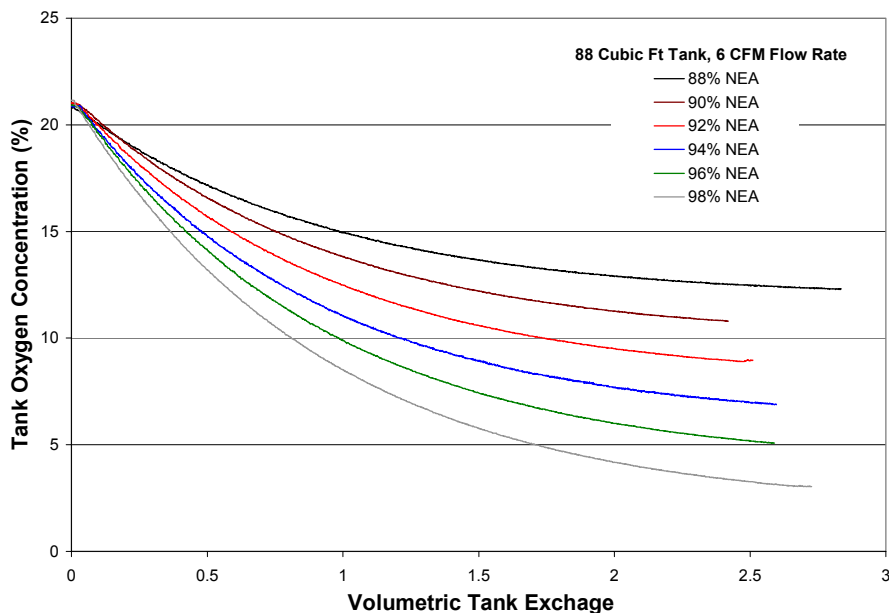

Figure 1. NEA Requirements for Inerting a Rectangular Fuel Tank Test Article

The effect of fuel on an adjacent inert ullage was studied by the FAA to determine how the off-gassing of air from fuel would effect the ullage oxygen concentration in the worst case, as well as for normal ground and flight conditions. Since commercial transport operations are not proposing scrubbing fuel (displacing the dissolved air with nitrogen), air dissolved in fuel could have a profound effect on an inert ullage during normal operations. Methods were developed to illustrate the maximum effect a fuel load can have on an adjacent inert ullage at different fuel loads (figure 2), starting oxygen concentrations, and altitudes. The test article was then subjected to a typical CWT ground/flight scenario (i.e., fuel load/burn, initial oxygen concentration, flight profile) at two different fuel loads. The results, which were validated with flight test data, illustrated that the effect of air entering the vent system due to normal fuel burn was far more significant than the effect of air evolution from the fuel on the oxygen concentration of the ullage [8].

To validate existing oxygen concentration requirements, the FAA conducted a series of ignition tests at reduced oxygen concentrations and various altitudes to determine the minimum oxygen concentration at which ignition could occur in a simulated aircraft fuel tank. The results validated the previous Kuchta data that stated at sea level the minimum oxygen concentration that could support a reaction with a significant pressure rise in a flammable ullage is approximately 12% by volume given a single high-power spark [9]. The data also illustrated that the minimum oxygen concentration increased with altitude to approximately 15% at 38,000 feet (figure 3).
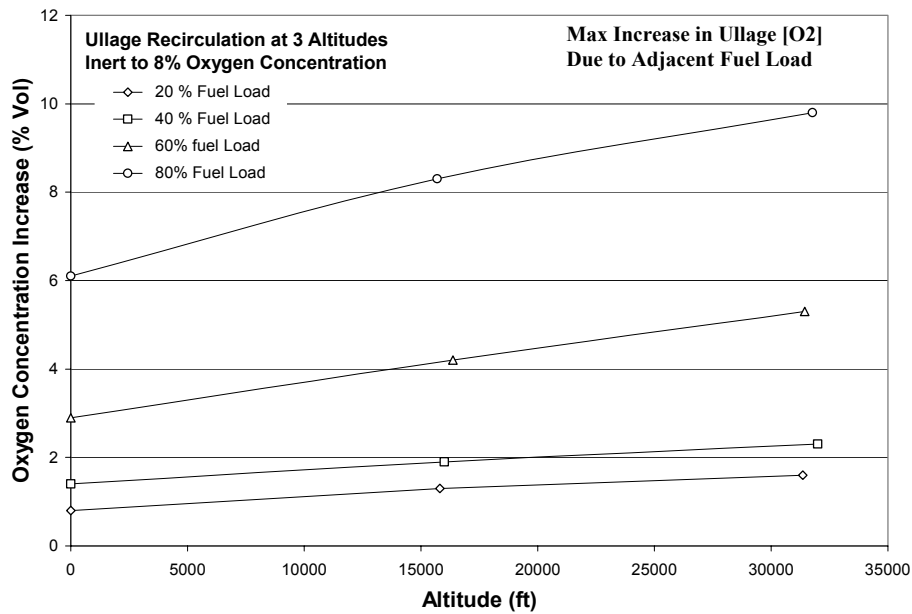
Figure 2. The Effect of Fuel Load on an Ullage Inerted to 8% with Increasing Altitude
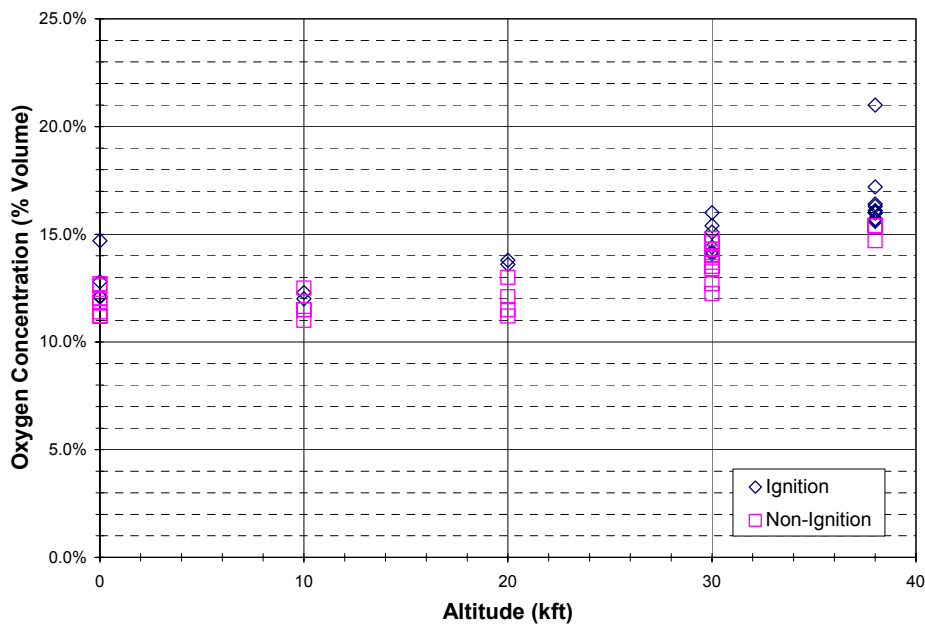

Figure 3. Lower Oxygen Concentration Limit Data for a Single High-Power Spark in an Ullage

EQUIPMENT AND PROCEDURES

Boeing 737-700 Test Article. For a proof of concept and demonstration of ground-based inerting, a Boeing 737-700 was provided by the Boeing Company for testing. The center wing tank holds 28,803 pounds of fuel (4,299 gals). It is contained in the center wing section of the aircraft, within the body and the inner sections of the wing root, often referred to as the cheek area. The empty CWT ullage volume is 598 normal cubic feet for the purpose of inerting the tank with NEA. The main tanks each hold 8,629 lbs of fuel (1,288 gals) and are contained entirely within the wings. The test aircraft CWT was modified with an NEA distribution manifold that distributed the NEA into the CWT in a relatively equal manner, allowing the CWT to be inerted with an external source.

To instrument the aircraft, Boeing personnel installed thermocouples and gas sample tubing in the CWT. The tank is divided into three major sections (center section, left cheek, and right cheek) with each section being separated into several bays. Figure 4 shows a top diagram of the CWT with numbers indicating the locations of the eight sample ports. The FAA developed a system to continuously measure the oxygen concentration at the eight identified locations in the center wing tank. Basically, the system consisted of a regulated sample train with flow-through oxygen sensors and in-line and ancillary equipment. Two identical four-channel systems were developed. Each four-channel system was self-contained in a standard 19-inch half rack designed to meet the Boeing flight test airworthiness requirements. The data were acquired by a Boeing data acquisition system. Reference 10 gives a more detailed explanation of the test article.

For each test, the CWT was inerted to 8%, and after a brief settling period, the air-cycle machines (ACMs) were operated to simulate ground operations. The ACMs are located beneath the CWT and tend to heat any residual fuel in the CWT. For flight tests, the ACMs were operated for 20 minutes on the ground before the aircraft briefly taxied to a runway and took off. The aircraft proceeded to an altitude of 35,000 feet, as prescribed by air traffic control, and then did several standard maneuvers at altitude.
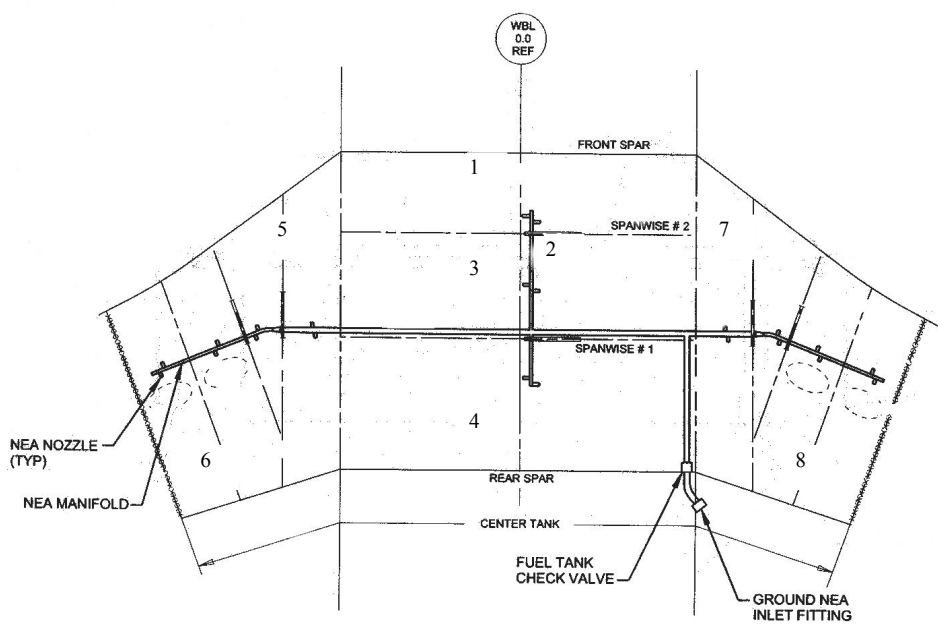
Figure 4. Boeing 737-700 CWT Plan View

Boeing 747SP Full-Scale Test Article. A Boeing 747SP was purchased to perform full-scale ground-inerting tests on a commercial transport airplane. It has four main wing fuel tanks, four wing reserve fuel tanks, and a large center wing fuel tank (CWT). The CWT is approximately 242 inches long and 255 inches wide with a height varying from 78 to 48 inches. As shown in figure 5, the CWT has six bays, two are the full width of the fuselage and four are two full-length bays bisected midway with a partial rib. The front spar and spanwise beam 3 form a large dry bay forward of the tank. The CWT is vented to the wing tip surge tanks via a vent channel in the wings by vent tubing contained within the tank. All fuel tanks are vented to one or both of the surge tanks, which act to catch fuel overflow and vent to the aircraft exterior via a NACA scoop. Reference 11 gives a more detailed description of the test article and the 747SP CWT. Figure 6 shows a top diagram of the 747SP CWT, illustrating the bay layout and numbering convention.

The 747SP full-scale test article has been instrumented with gas sample plumbing and thermocouples in the CWT to allow for the measurement of inerting and flammability parameters during normal ground operation conditions [11]. The test article can be supplied with inert gas produced by an industrial NEA generator at varying purities (oxygen concentration). The aircraft CWT is plumbed with a deposit manifold that deposits all the NEA into bay 3 (figure 6). This method was established in scale testing as an efficient

4

(least amount of NEA) method of inerting the tank while still providing acceptable gas distribution from bay to bay [12].
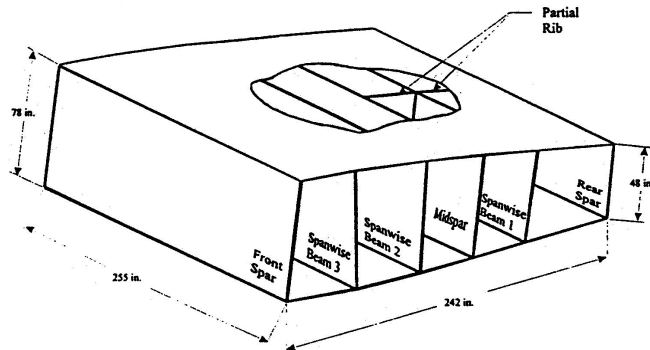

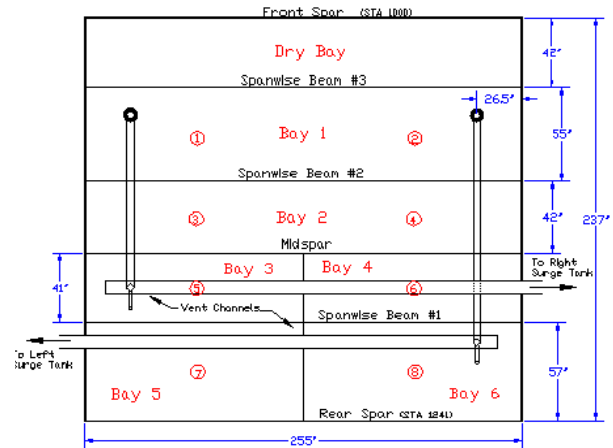**Figure 5. Center Wing Tank Off-Axis View**

Figure 6. Top Diagram of Center Wing Tank with Eight Oxygen Sample Port Locations and Bay Numbering Convention

    <u>Twenty-Four Percent Scale Tank.</u> To model inert gas distribution in the 747SP test article CWT, a scale CWT model was constructed from plywood using drawings from a NTSB report detailing work done on scale modeling of explosive events in a 747 CWT [13]. The tank was built to 24% length scale. Each spanwise beam, spar, and partial rib was also scaled as well, with all penetration holes being scaled in terms of relative area. The vent system was also modeled with PVC tubing and aluminum box channel. NEA could be deposited in each bay at rates between 8 and 380 CFH. The tank uses the same bay numbering convention as the full-scale aircraft but has only one gas sample port in the center of each bay. Reference 12 gives a complete description of the scale tank test apparatus and instrumentation with diagrams and photographs and includes the drawings of the tank profile with accompanying spars, spanwise beams, and ribs.

ANALYSIS AND MODELING

    <u>Data Reduction Methods.</u> Volumetric tank exchange (VTE) is defined as the volume of deposited inert gas divided by the ullage volume. This dimensionless parameter allows for the comparison of inerting of different volume tanks at different flow rates.

$$Volumetric\ Tank\ Exchange\ =\ \frac{Time*Volume\ Flow\ Rate}{Fuel\ Tank\ Volume} \tag{1}$$

    When comparing different methodologies of inerting a 747SP CWT, it is convenient to be able to express the average oxygen concentration in the tank, even though the concentrations of the individual bays often vary. To achieve this, a weighted average by volume can be calculated at a given time. This average weighed the oxygen concentration of each bay with the volume percentage of each bay.

$$Average\,[O_2]\ =\ 0.31[O_2\,Bay1]+0.23[O_2\,Bay2]+0.10[O_2\,Bay3]+0.10[O_2\,Bay4]+0.13[O_2\,Bay5]+0.13[O_2\,Bay6] \tag{2}$$

    Inerting ratio is a nondimensional representation of oxygen concentration defined as the difference between the ullage oxygen concentration and ambient divided by the difference in the inert gas oxygen concentration and ambient [7].

$$Inerting\ Ratio\ \ =\ \ \frac{[O_{2\,Amb}]-[O_2(t)]}{[O_{2\,Amb}]-[O_{2\,NEA}]} \tag{3}$$

With: $O_{2\,Amb}$ = Oxygen Concentration of Ambient Air

               $O_{2\,NEA}$ = Oxygen Concentration of Inerting Gas

               $O_2(t)$ = Oxygen Concentration of the Ullage

Given the perfect mixing solution derived in reference 7 relating inerting ratio to VTE, the following equation for inerting ratio in terms of VTE and inerting efficiency k is intuitive.

$$Inerting\ Ratio\ \ =\ \ 1-e^{-k*VTE} \tag{4}$$

By assuming the inerting process follows this equation, inerting efficiency can be calculated, given a VTE and inerting ratio at any point in the inerting process. Solving the above equation for k gives the following.

$$k\ \ =\ \ -\ \frac{\ln(1-Inerting\ Ratio)}{VTE} \tag{5}$$

By using the calculated k value, given the resulting oxygen concentration and VTE of an inerting process, equation 3 can be redimensionalized similar to the method in reference [12]. A curve can be generated illustrating the relationship between average ullage oxygen concentration and VTE for a given k.

$$O_2(t)\ \ =\ \ O_{2\,Amb}-\ [(O_{2\,Amb}-O_{2\,NEA})(1-e^{-k*VTE})] \tag{6}$$

<u>Engineering Model.</u> An engineering model was developed to simulate oxygen concentration evolution during uneven inert gas deposit in a fuel tank with multiple compartments. This model was based on a single-bay tank model that tracked the volume of oxygen in the tank and calculates the volume fraction, given the total tank volume. The model assumed a homogenous ullage with good mixing at every time step and runs in a spreadsheet format instantaneously. This methodology has proved effective at modeling inerting of a simple rectangular box with a single deposit and a single vent [7]. To apply this principal to inerting a multiple-bay tank, assumptions must be made about the path of the flow. The focus of the modeling effort was to model the inert gas distribution in the full-scale 747SP test article. The test article has a single deposit of gas in bay 3 and a vent exit port on the right sides of bays 1 and 6. Based on this information, the inert gas flow pattern was assumed using and is shown in figure 7. All places where flow is split between multiple bays, the ratio of the cross- sectional flow areas between the different bays is used to weight the amount of flow to each bay. The multiple-bay model calculates the volume of oxygen in each bay in time, using the principals expressed in equation 7. Reference 11 discusses the modeling technique more completely.

$$V_{O_2}(t)\ =\ V_{O_2}(t-1)\ +\dot{Q}_{NEA}*\Delta t*IGOF\ +\dot{Q}_{Bayn}*\Delta t*V_{O_2 Bayn}(t-1)/V_{Tank}\ -\dot{Q}_{sum}*\Delta t*V_{O_2}(t-1)/V_{Bay} \tag{7}$$

where: $V_{O_2}(t)$ = Volume of oxygen in a given bay at time t Δt = Time step

      $\dot{Q}_{NEA}$ = Flow rate of inerting gas into a given bay V_{Bay} = Volume of a given bay

      $\dot{Q}_{sum}$ = Sum of all the flow rates into a given bay $IGOF$ = Fraction of oxygen in inert gas

      $\dot{Q}_{Bayn}$ = Flow rate from surrounding bay n V_{Bayn} = Volume of surrounding bay n
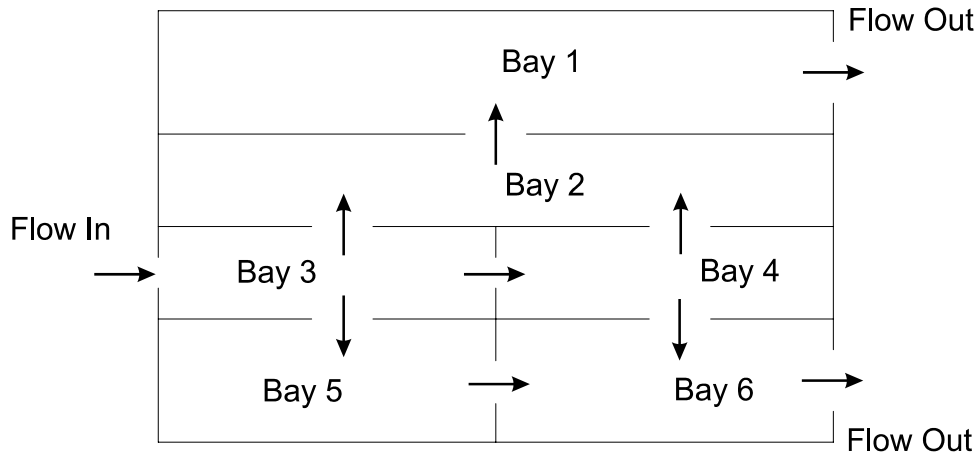
Figure 7. Diagram of Engineering Model Flow Pattern

Computational Work. To gage the ability of complex analysis tools to accurately simulate oxygen concentration evolution during uneven inert gas deposit into a fuel tank with multiple compartments, a computational fluid dynamics (CFD) model was developed with the CFD package FLUENT. This modeling tool has the ability to track fluid species and uses a finite volume method where the general conservation (transport) equation is solved for each finite volume cell. The model was solved using a laminar flow throughout so that oxygen evolution is based entirely on diffusion of the different gas species. The model developed had over 700K nodes and ran on a computational computer for 2-3 days.

RESULTS

Boeing Flight Test. Figure 8 shows a plot of average oxygen concentration measured on the 737 test aircraft versus VTE during a ground test. This case was for an empty tank (0% fuel) and 95% NEA at a flow rate of 90 CFM. The inerting data are compared with the exact and empirical solutions in reference 7. This graph illustrates a VTE of 1.75 required to achieve 8-percent oxygen concentration, which is slightly greater than the theoretical value given by the exact solution (1.7) and significantly greater than the empirical relationship that results in a VTE of 1.5.
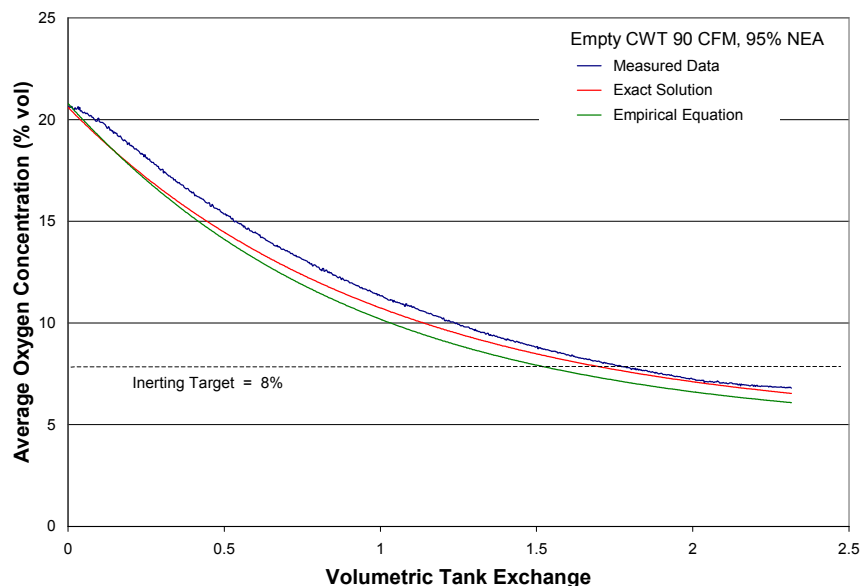

Figure 8. Average Oxygen Concentration Measured from Inerting a Boeing 737 CWT

The results of the GBI demonstration tests on the 737, with quiescent wind conditions, resulted in no measurable change in average ullage oxygen concentration during the 2-hour period following inerting of the CWT. Figure 9 gives the average oxygen concentration measured in the three main areas of the tank during the 2-hour period following a subsequent CWT inerting with simulated wind on the right vent. This test was designed to illustrate a potential ground wind condition that could disperse the NEA in the CWT. Although under quiescent conditions, the NEA dispersed very little (not measurable), the simulated crosswind had a profound effect on the average oxygen concentration in the left cheek area, which is where the right wing vent opens to the CWT. The average oxygen concentration in the left cheek reached 12% in approximately 35 minutes, illustrating a need to limit cross-venting of a CWT under some conditions of GBI for aircraft with cross-vented fuel tanks. Figure 10 compares the average CWT oxygen concentration for the two tests.
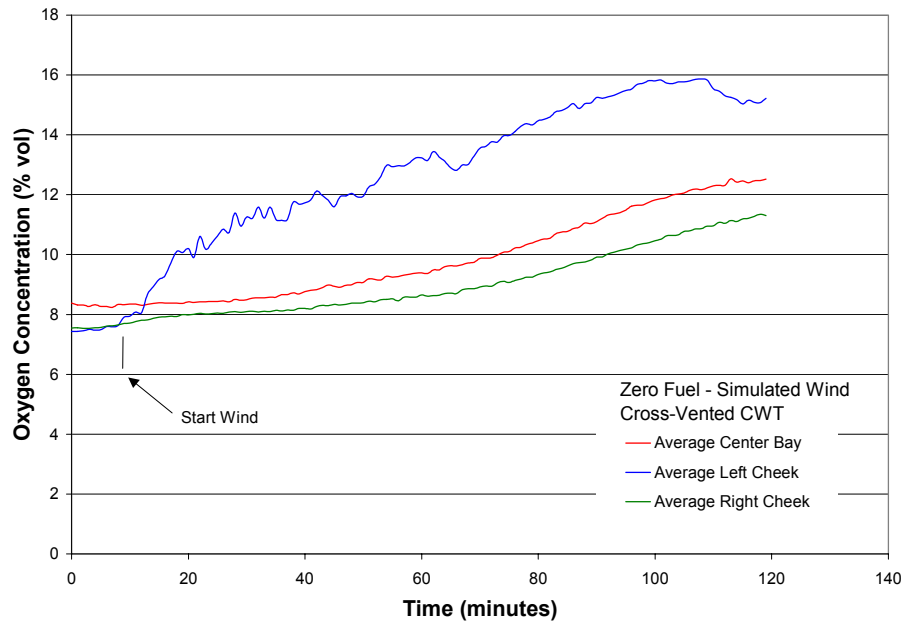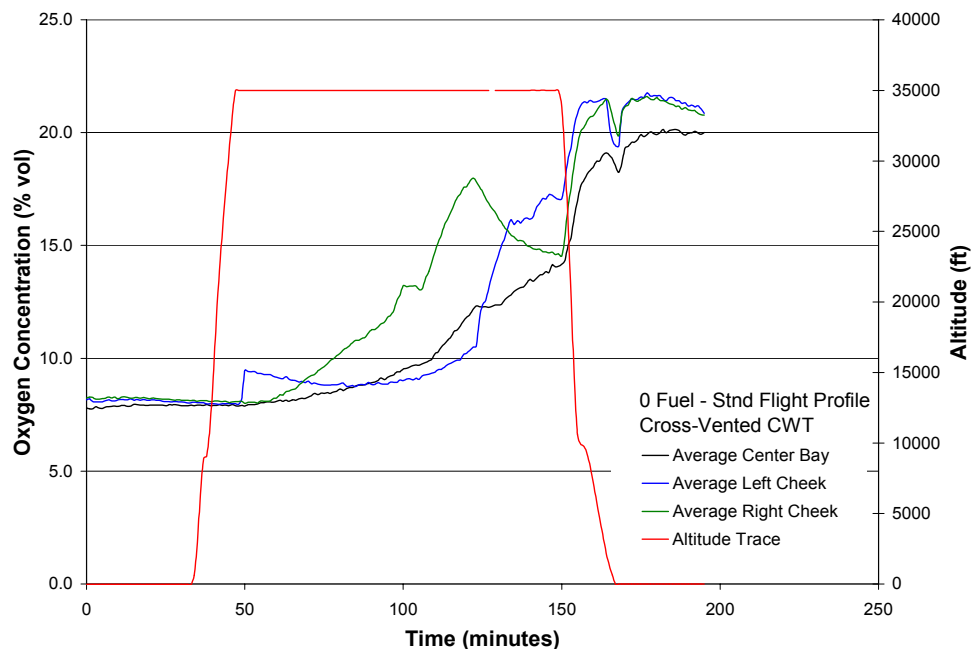

Figure 9. CWT Oxygen Concentration Dissipation From Simulated Wind on a Boeing 737 CWT
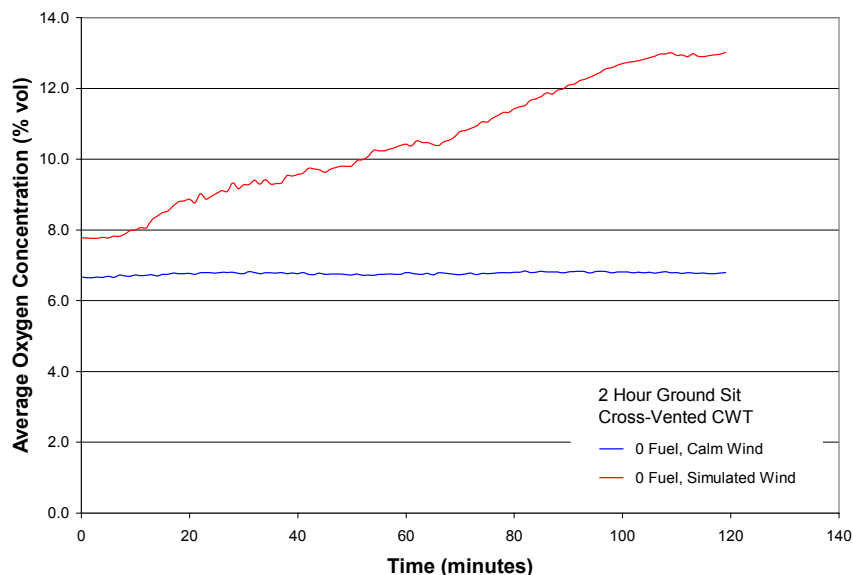
Figure 10. CWT Oxygen Concentration Dissipation for Different Ground Wind Conditions on a Boeing 737 CWT in a Cross-Vented Configuration

The effect of the cross-venting configuration on the diffusion of NEA from the CWT of the 737 test aircraft was examined in a flight test. Figure 11 illustrates the profound effect of these maneuvers. During the test, the pilot also trimmed the aircraft in an intentional side-slip to maximize the effect. This data illustrates that the average right cheek area oxygen concentration of the CWT was less then 12% for approximately 50 minutes at cruise altitude.
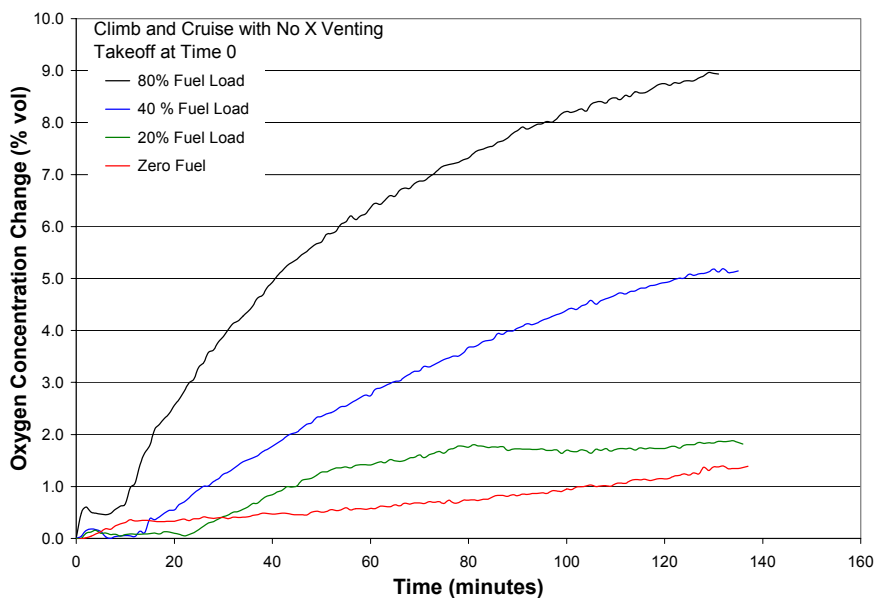

Figure 11. CWT Oxygen Concentration Dissipation for a Typical Flight Profile on a Boeing 737 CWT with Cross-Venting

This test was repeated after an aircraft modification was performed to prevent cross-venting of the CWT by blocking one vent channel. The pilot repeated the flight profile and test procedures as best as possible. Figure 12 illustrates the effect of the elimination of cross-venting on the ability of the tank to remain inert during normal flight operations. The average oxygen concentration in each section remained below 12 percent for the entire flight until descent, highlighting the effect of eliminating cross-venting on maintaining a low oxygen concentration in a fuel tank during flight operations after GBI. During descent, the oxygen concentration of the tank rose sharply, as outside air rushed in the vents to equalize the pressure between the outside and inside of the tank.

Using the CWT fuel also has a considerable effect on the oxygen concentration in the CWT. As fuel is consumed from the CWT during flight or ground operations, air is drawn into the vent to equalize pressure, resulting in a higher ullage oxygen concentration. Figure 13 gives the average ullage oxygen concentration increase measured during four different fuel load flight tests. Initially, each ullage oxygen concentration was approximately 8 percent and each flight test had approximately the same flight profile. Although the increase is substantial for the higher fuel loads (40- and 80-percent full), the increase in oxygen concentration during the flight phase for the 0- and 20-percent fuel loads was minimal. It has been hypothesized that these lower fuel loads pose a higher risk to commercial operations, as small fuel loads heat easier and would tend to be more flammable.
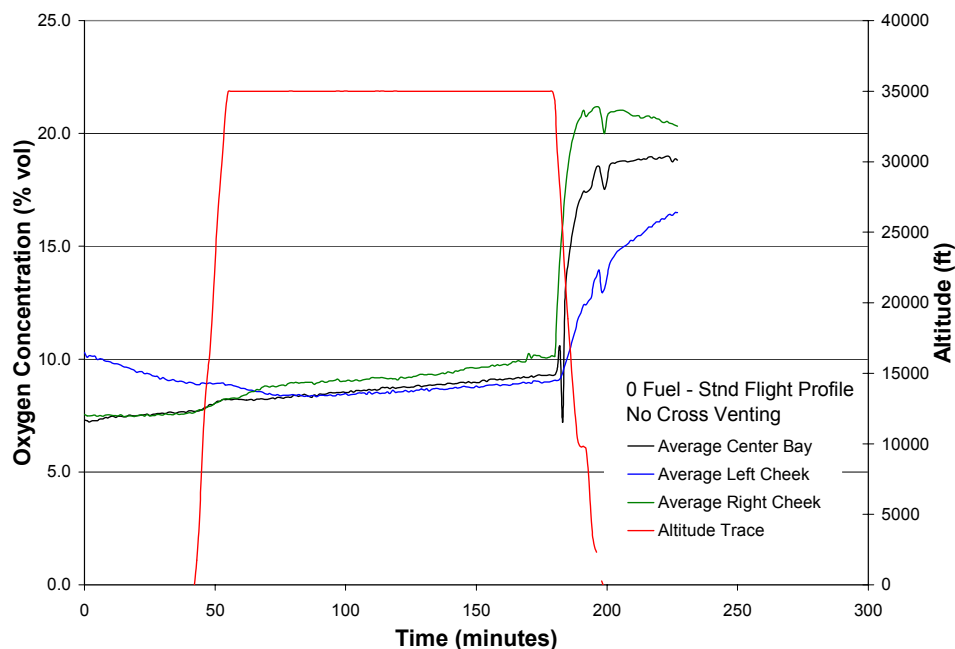
Figure 12. CWT Oxygen Concentration Dissipation for a Typical Flight Profile on a Boeing 737 CWT Without Cross-Venting


Figure 13. CWT Oxygen Concentration Dissipation at Different Fuel Loads for a Typical Flight Profile on a Boeing 737 CWT

Full-Scale Ground-Based Inerting. Due to operational problems during the GBI demonstration testing on the 737-700, only a limited amount of data was acquired to realistically simulate ground-supplied inerting of a complex compartmentalized tank. The gas was distributed with a relatively complex distribution manifold that deposited inert gas equally around the tank volume. This data suggested that a slightly greater amount of NEA would be required to inert the tank than was determined in reference 7. To acquire more full-scale GBI data the FAA performed testing on the 747SP ground-test article using a simple deposit system (single deposit in bay 3).

Figure 14 illustrates the individual bay oxygen concentrations measured during inerting of the 747SP test article with the single-bay deposit methodology. The CWT required a VTE of 1.3 to reach an overall average oxygen concentration (volumetric average) below 8 percent by volume. This is a significant improvement over the 1.5 to 1.6 numbers calculated from measurements in reference 7. This illustrates the increased efficiency of the localized deposit methodology, which tends to vent more air from bays 1 and 6 (exit bays) before the inert gas mixes into those bays and begins to vent.

Initially, the inerting process efficiency varied from test to test in the 747SP test article. This prompted further investigations which determined that inert gas was tending to localize at the top of the tank, leading to a lower oxygen concentration at the top of the tank. This decreased the efficiency of the inerting process as the inert gas is deposited in and vented from the top of the tank. This phenomena is complicated by the fact that the sample system only samples from the top of the tank, which gives a biased picture of inerting when comparing data from simple tanks, scale testing, and the Boeing flight test (see figure 15). Observed increases in some bay oxygen concentrations after starting the ACMs was attributed to this stratification. Figure 15 illustrates that the good mixing inerting data from the 747SP testing follows the same trends as previous data but is slightly more efficient as predicted. However, 747SP quiescent inerting data did not follow this general trend and resulted in higher oxygen concentrations when ACMs were operated after inerting was complete. Although running the ACMs during inerting eliminated this problem, (see figure 14) this phenomenon was studied.
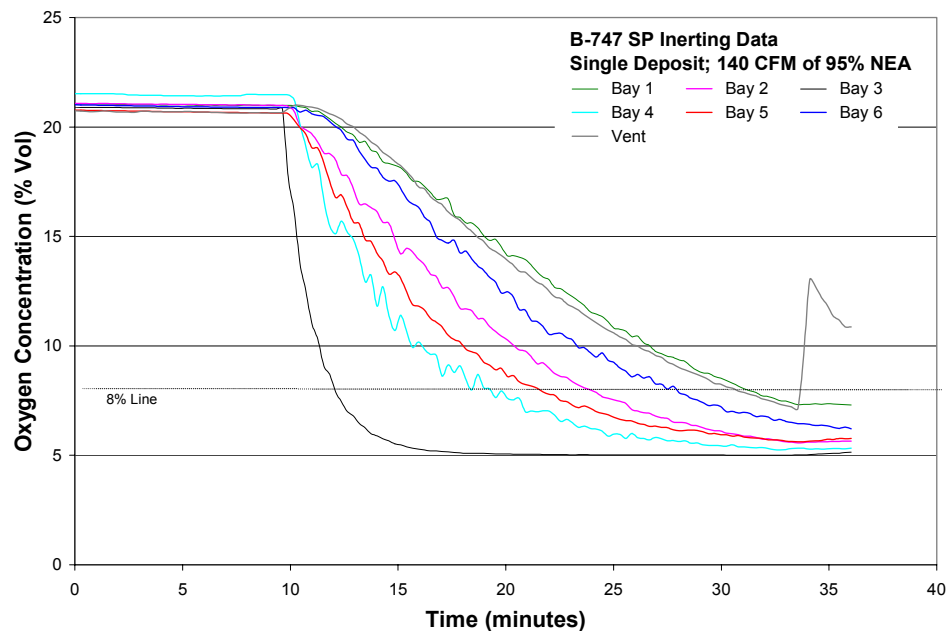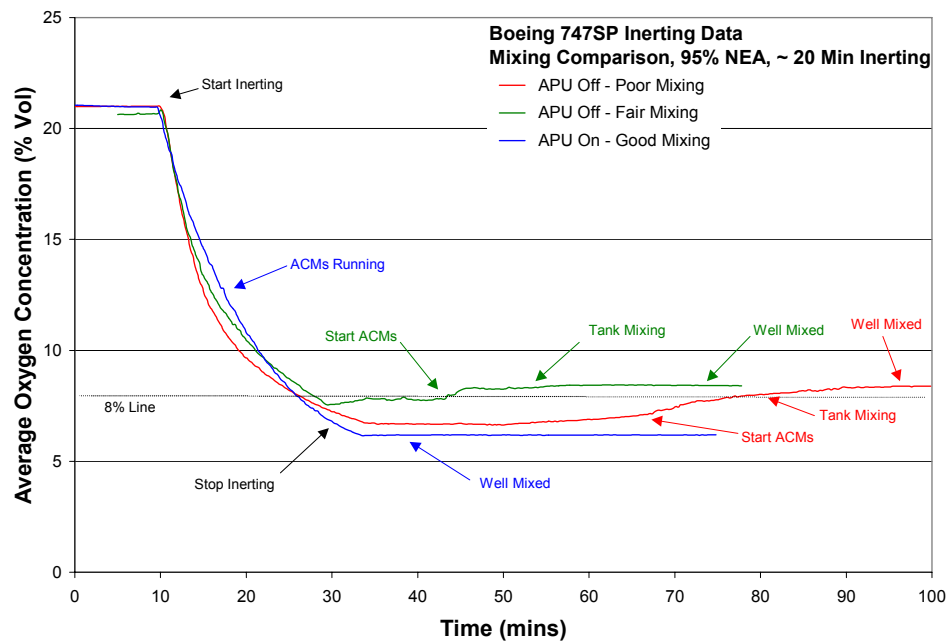

Figure 14. Boeing 747SP CWT Inerting Data for a Typical Ground-Supplied Inerting Test Using 95% NEA

Figure 16 gives the average CWT ullage oxygen concentration for three different tests on the 747SP before, during, and after inerting. The good mixing data was acquired with the ACMs running during the entire test and illustrates no rise in oxygen concentration after the inerting process is complete. The fair and poor mixing lines illustrate two different tests without stimulating vertical mixing during the inerting process. The increase in oxygen concentration that occurs, after starting the ACMs when inerting is complete, is attributed to mixing the ullage vertically and obtaining the resulting homogeneous oxygen concentration. Note that, although the two quiescent inerting tests deposited different quantities of gas (1.6 versus 1.9 VTE), they resulted in the same final oxygen level, showing the unpredictability of the process when vertical mixing is not stimulated.
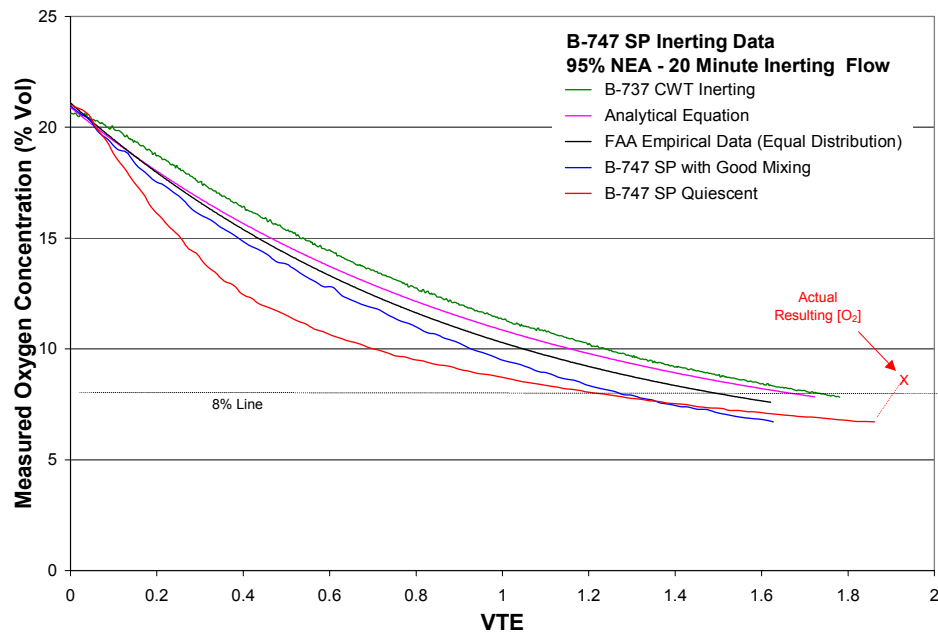
Figure 15. Average Oxygen Concentration Data for Different Mixing Scenarios

**Figure 16. Boeing 747SP CWT Inerting Data for a Different Mixing Scenarios**

To quantify what this effect could have on an aircraft being inerted under quiescent conditions, an inerting coefficient was developed and calculated, given the perfect mixing solution discussed in reference 7. Using the resulting oxygen concentrations (after running the APU), k values were calculated and applied to equation 6 to obtain the curves seen in figure 17. This represents the extent of inert gas requirements measured on the 747SP test article to date. Although good mixing required only a VTE of 1.2 to 1.3 to reach an average oxygen concentration of 8%, the worst observed case would have required a VTE of approximately 2.0. This highlights the importance of ensuring good mixing at the inert gas deposit locations in a fuel tank ullage. Improved orientation and design of the deposit nozzle should eliminate this problem of poor mixing, but more work is required to validate the practicality of increasing vertical mixing when performing quiescent inerting.

12
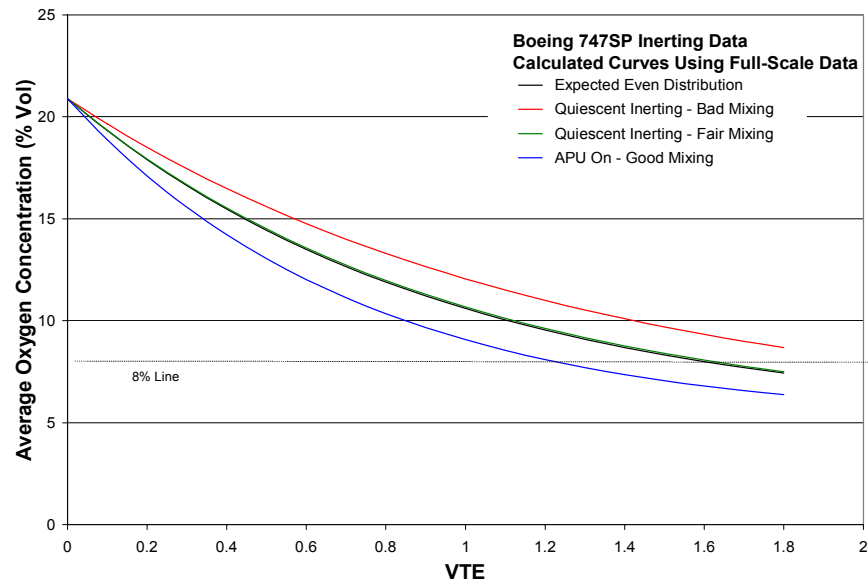
**Figure 17. Predicted Inerting Curves for Different Inerting Efficiencies**

Inert Gas Distribution Modeling. Inerting results from 747SP full-scale testing were compared with the scale tank data as well as the engineering model developed to simulate the distribution of inert gas in a six-bay, compartmentalized tank. Dimensionless results from the CFD analysis were also compared with the data.

Figure 18 compares the results from inerting the full-scale test article with the scale plywood tank in terms of volumetric tank exchange (VTE). The data compare very well, illustrating the ability of a scale tank to simulate global flow behavior in a large confined tank given low-pressure flows and good mixing. This is probably because the velocities and pressures in the scale tank allow for inerting gas volume flow ratios from bay to bay to duplicate the full-scale test article. Since volume flow from bay to bay is the primary driver of oxygen concentration change in each bay, the scale tank duplicates the inerting gas distribution of the aircraft well [11].
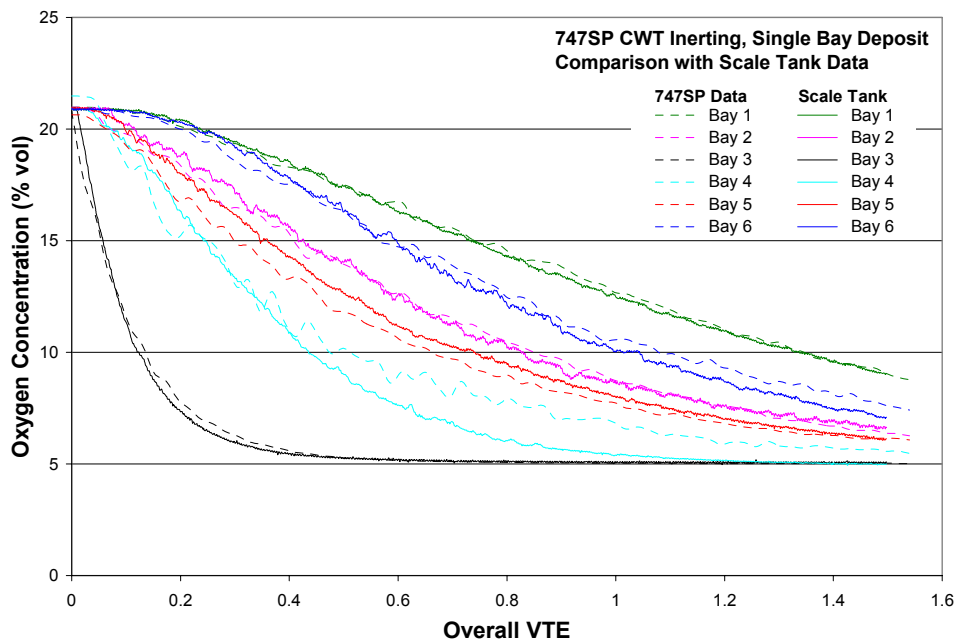
Figure 18. Comparison of Full-Scale 747SP CWT Inerting Data With Scale Tank Results

The results from the engineering model were also compared with the full-scale inerting data in figure 19. This illustrates the ability of a simple spreadsheet simulation to duplicate the inerting flow distribution in a compartmentalized tank. The data compare fair, although some bays are considerably different. It is counter-intuitive that bay 1 models relatively well, while bay 6 models relatively poorly. All inert gas flow passes through bays 1 or 6 before exiting. Therefore, by the model design, inert gas can either flow to bay 1 or 6.   If bay 1 gets the correct amount of inert gas flow to reduce the oxygen concentration in the same manner as the full-scale test article, bay 6 should also. This difference is probably the result of sensitivity of the oxygen concentration change to the bay volume [11]. Bay 4 models relatively poor for all modeling methods.
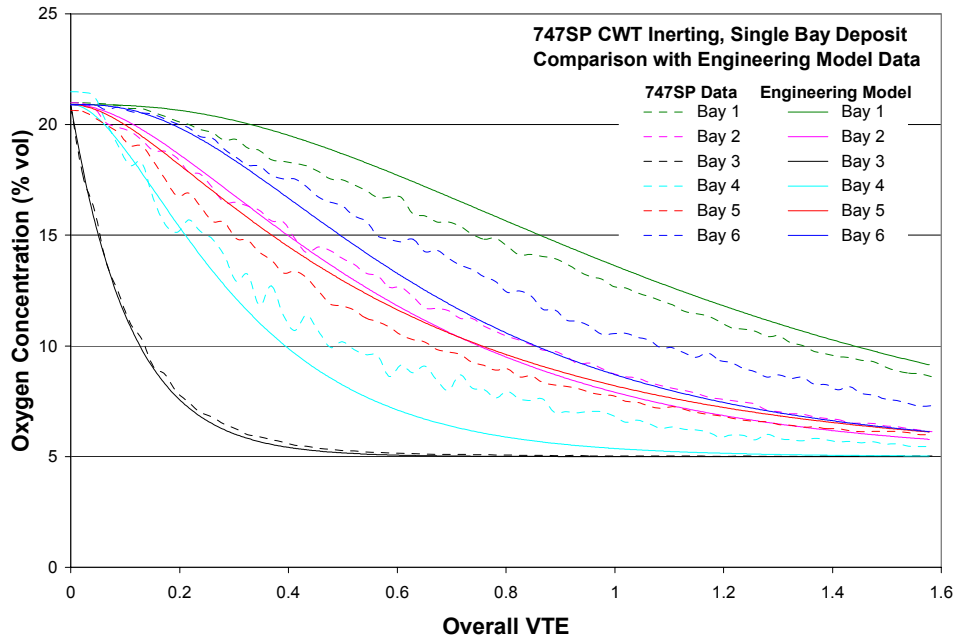

Figure 19. Comparison of Full-Scale 747SP CWT Inerting Data with the Engineering Model

Figure 20 compares the results of the CFD analysis with the full-scale test data. The CFD model was actually designed to model the scale CWT model, but is compared to the full-scale test article to illustrate the point. Like the scale tank data, the CFD model comparisons are good with the exception of bay 4. The resulting magnitudes of bay oxygen concentrations are very close to the full-scale data illustrating the capability of the modeling method.

Figure 21 gives the volume weighted average oxygen concentration of the tank ullage for each modeling method discussed compared with the full-scale test article data. The results compare very well in that all modeling methods predict the same amount of inert gas required to reach 8% oxygen concentration as measured on the full-scale test article. Each modeling effort represents a different level of complexity and resource requirements, with the resulting cost of each being an order of magnitude different. This is to say, the engineering model is the least costly and resource intensive, with the scale tank being an order of magnitude more complex and expensive, and the CFD analysis being the most costly and resource intensive.
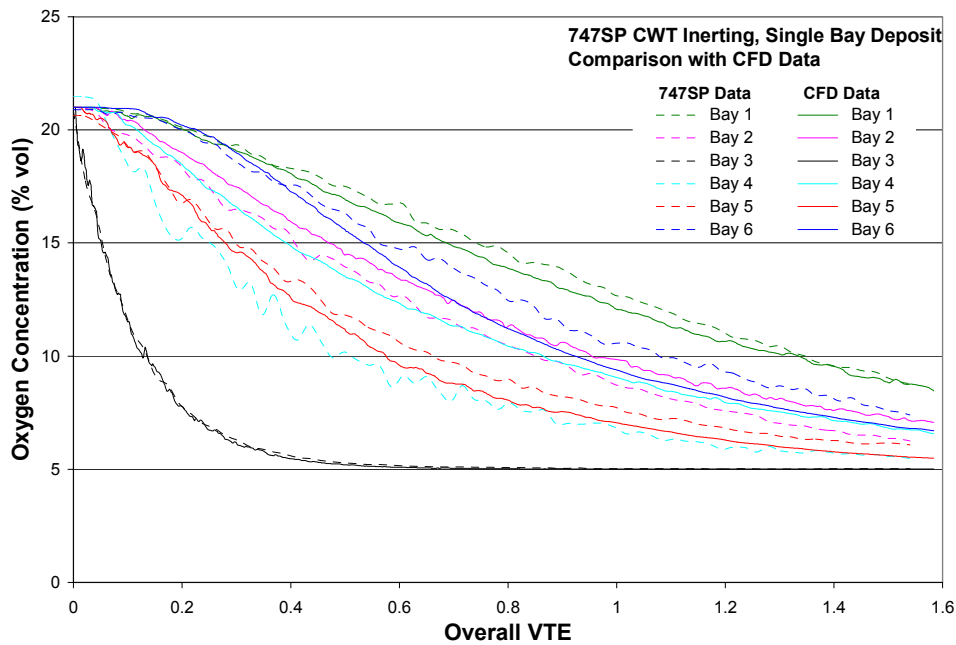
Figure 20. Comparison of Full-Scale 747 SP CWT Inerting Data With the Results of a CFD Analysis Results
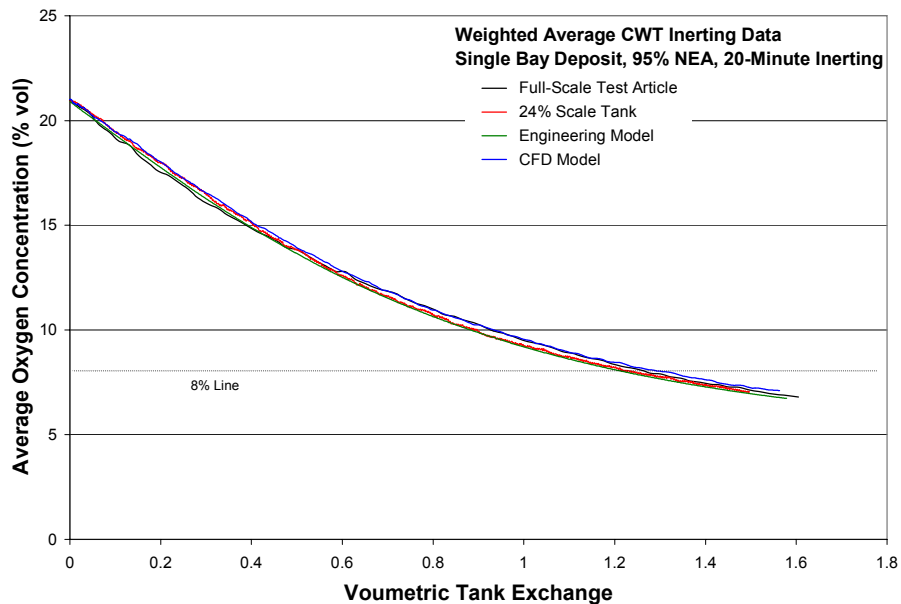
Figure 21. Comparison of Weighted Average Ullage Oxygen Concentration Data for the Scale Tank and Engineering Model With the Full-Scale Test Article

SUMMARY

In summary, GBI is an effective methodology for reducing the flammability of heated center wing tanks in the commercial transport fleet. It provides significant protection against an inadvertent ignition of a center wing tank during the operational times that have the greatest risk of a flammable ullage. This methodology does have limitations in its ability to be flexible and has extensive nonrecurring labor costs. It is for these and other reasons that GBI may not be cost-effective. Recent improvements in hollow fiber membrane technology and advances in system methodologies has yielded new onboard inert gas generation system (OBIGGS) designs that could prove to be effective at reducing the fleetwide flammability in a cost-effective manner.

Plans to apply this and additional research to the design, construction, integration, and testing of a commercial transport OBIGGS in the near future will allow for potentially greater fleetwide protection at an even lesser cost.

REFERENCES

1. "Fuel Tank Harmonization Working Group Final Report," Aviation Rulemaking Advisory Committee, July 1998.

2. "Fuel Tank Inerting Harmonization Working Group Final Report," Aviation Rulemaking Advisory Committee, February 2002.

3. MacDonald, J. A. and Wyeth H. W. G., "Fire and Explosion Protection of Fuel Tank Ullage," Ministry of Aviation Supply, Engineering Physics Department, Royal Aircraft Establishment, Farnborough, England.

4. Klueg, E. P., McAdoo, W. C., and Neese, W. E., "Performance of a DC-9 Aircraft Liquid Nitrogen Fuel Tank Inerting System," FAA Report FAA-RD-72-53, August 1972.

5. Stewart, Paul B. and Starkman, Ernest S., "Inerting Conditions for Aircraft Fuel Tanks," WADC Technical Report 55-418, September 1955.

6. Kuchta, Joseph M., "Oxygen Dilution Requirements for Inerting Aircraft Fuel Tanks," Second Conference on Fuel System Fire Safety, Federal Aviation Administration, May 1970.

7. Burns, Michael and Cavage, William M., "Inerting of a Vented Aircraft Fuel Tank Test Article with Nitrogen Enriched Air," FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ DOT/FAA/AR-01/6, February 2001.

8. Cavage, William M., "The Effect of Fuel on an Inert Ullage in Commercial Transport Airplane Fuel Tanks," FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ, To be published.

9. Summer, Steven, "Limiting Oxygen Concentrations Required to Inert Jet Fuel Vapors Existing at Reduced Fuel Tank Pressures," FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ DOT/FAA/AR-02/79, To Be Published.

10. Burns, Michael and Cavage, William M., "Ground and Flight Testing of a Boeing 737 Center Wing Fuel Tank Inerted with Nitrogen-Enriched Air," FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ, DOT/FAA/AR-01/63, August 2001.

11. Cavage, W. M., "Modeling Inert Gas Distribution in Commercial Transport Aircraft Fuel Tanks," Paper presented at 22nd AIAA Advanced Measurement Technology/Ground Testing Conference, AIAA 2002-3032, June 2002.

12. Cavage, William M. and Kils, Ole, "Inerting a Boeing 747SP Center Wing Tank Scale Model with Nitrogen-Enriched Air," FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ, DOT/FAA/AR-02/51, May 2002.

13. Shepherd, A., E., et al., "Jet A Explosions – Field Test Plan ¼-Scale Experiments," TWA 800 Simulation Flight," TWA Flight 800 Docket Materials DCA-96-MA070, Docket No. SA-516, Exhibit No. 20E, August 2000.